

Technological Progress and Investment: A Non-Technical Survey

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Abstract

This paper presents a non-technical overview of the recent investment literature with a special emphasis on the connection between technological progress and the investment decision. First of all, we acknowledge that some dramatic advances have been made in the 1990s in understanding and modelling non-convex capital adjustment schemes and irreversibility. Nonetheless, this new literature has not always satisfactorily accounted for the investment-specific (or embodied) nature of technical progress. We argue that the recent technological trends towards more embodiment have had a heavy impact on the way the investment decision is taken and is to be taken. This in turn should imply the reconsideration of many empirical results, and a more careful modelling strategy taking into account the price variables and scrupulously choosing the most appropriate level of (dis)aggregation.

Keywords: Investment, Technological progress, Non-convex adjustment, Irreversibility, Embodiment

Journal of Economic Literature: E22, E32, O40.

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1 Introduction

”Economic Theory can give reasonably good account of how the level of investment influences effective demand and employment. If only we knew more about the determinants of investment! But unfortunately, our knowledge in this direction is still very meager. One might well ask, What is wrong with the theory of investment? Or perhaps, what is wrong with the subject matter itself! For one thing, this variable - the pivot of modern macroeconomics- has apparently lived a somewhat nomadic life among the various chapters of economic theory. Perhaps it has not stayed long enough in any one place. Perhaps it has been ill treated” (Haavelmo, T. (1960) *A Study in the Theory of Investment*, pp.3)

With this astonishing paragraph, Haavelmo (1960) begins his famous book *A Study in the Theory of Investment*, a prime example of the state-of-the-art of Investment Theory in the early 1960s. Many surveys on the subject have appeared since then (for instance, Jorgenson, 1963; Chirinko, 1993; Caballero, 1999) and economic theory has made an incredible step towards a more comprehensible understanding of this important variable. Yet in 2000, Caballero, one of the most important researchers in the field, opened his talk ”Aggregate Investment: Lessons from the Previous Millennium” with the following statement:

”But while we all may agree on the importance of investment for a nation’s economic health, our understanding of its determinants, both at the microeconomic as well as the macroeconomic level, has remained limited. The empirical investment literature has been nearly merciless in evaluating investment theories.” (Caballero, R. 2000 American Economic Association Session. In Memoriam: Robert Eisner, pp 1-2)

This pessimistic view about the evolution of our knowledge about investment might be influenced by the fact that researchers have been quite unsuccessful in empirically forecasting this component of aggregate demand. One can observe that heuristic models, such as accelerator models, have shown to be empirically better adjusted than models based on micro-foundations. The apparent superiority of heuristic models should not lead us to forget about price variables and Tobin’s “q” when talking about investment. First of all, the superiority of estimated accelerator models, for example, does not mean

that we already understand how the investment decision is made and how this decision is oriented by economic policy; there is not a theory behind the accelerator, it's just a technique that apparently works in some circumstances and that has its own problems (see Oliner, Rudebusch and Sichel, 1995, for example). Second, the bad empirical performances of optimal control-based investment models can be also partially attributed to the way they are tested in practice. For example, the way the rate of capital depreciation is traditionally treated in econometric applications is highly questionable, especially during the 1990s, as it does not accurately capture the pace at which capital goods actually become obsolete.

It seems therefore overwhelmingly clear that the traditional user cost and Tobin's q models are too much "stylized" to serve as universal and unquestionable models of both microeconomic and aggregate investment. There is an urgent need to profoundly study and document how the investment decision is effectively taken in real life over a wide variety of microeconomic cases. **In particular, a much closer inspection into how the capital adjustment processes actually take place is required, especially in connection with the pace of technological progress.** This calls for two major focuses:

a) In the traditional optimal control theory developed (see for instance Chirinko (1993)), the capital adjustment issue is settled by setting a *convex* adjustment function, usually a quadratic function for tractability. But is adjustment gradual in real life? The answer is definitely no. It is now known that investment at the firm level is lumpy and infrequent (Doms and Dunne, 1998), and that these two characteristics are unlikely to completely disappear in the aggregate (Cooper, Haltiwanger and Power, 1999). Doms and Dunne worked on the investment patterns of 12 000 plants in US manufacturing over the interval 1972-1989. For each firm, they constructed a series of the proportion of the total equipment investment of the firm. It turns out that the largest investment period accounts on average for more than 25 percent of the 17 year of investment. Moreover, more than half of the firms exhibit a capital growth of about 50 percent in a single year. Also, the second largest investment spike often comes next to the largest investment, which suggest that the two biggest spikes correspond to a single investment episode. Finally, Doms and Dunne studied the correlation between aggregate investment (summing up the investments done by all the establishments of their sample) and an

index of microeconomic investments and showed that it is actually very high.

b) Recent empirical studies confirm that the Information and Communication Technologies (ICT hereafter) burst in the 1990s has considerably distorted the investment behavior at all levels: The associated dramatic decrease in the relative price of capital during the 1990s has rehabilitated price variables as a major determinant of investment decisions (see for instance Tevlin and Whelan, 2003). This has led some authors like Whelan (2002) to advocate another empirical appraisal of the investment decision, based on a two-sector accounting benchmark model in order to reflect the pace of the relative price of capital and the very fast depreciation of an increasingly large fraction of the capital stock. At the same time, another complementary view of investment emerged, resurgence of the vintage capital theory of the sixties: investment and technological innovations are not "separated", investment is the unique vehicle of innovations decisions, as Greenwood and Jovanovic (2001) observe:

"In reality, advances in technology tend to be embodied in the latest vintages of capital. This means that new capital is better than old capital, not just because machines suffer wear and tear as they age, but also because new capital is better than the old capital was when the latter was new. It also means that *there can be no technological progress without investment*" (pp. 179-180, Italics ours).

In this paper, we carefully review the state of art of the literature investment regarding these two fundamental aspects. We start by a non-technical discussion of the "new" investment theories which have recently introduced non-convex adjustment costs and irreversibility in the heart of investment theory (Section II). We first notice that these theories have considerably improved our understanding of how the investment decision is taken both at the plant and the aggregate levels. However, we also observe that, with some very few exceptions, the modelling of technological progress in such theories is not markedly different from traditional "exogenous" modeling in the neoclassical model; the whole action inherent in these theories come from non-convex adjustment and other ingredients like irreversibility. Nonetheless as outlined just above, there are plenty of microeconomic and macroeconomic studies pointing at a significant change in the composition of technological progress after the 60s, and showing that embodiment should be seriously accounted for, especially in the computer era. We therefore end the survey with a detailed non-technical exposition on modelling embodiment both at

the micro and macro level, and on the methodological consequences of the information technologies boom in the 1990s (Section III).

2 Characterization of microeconomic adjustment

As we have mentioned in the introduction, there is a compelling evidence that investment patterns at least at the plant level are far from gradual, which goes at odds with the optimal control investment model with convex adjustment costs. How could the economic theory deal with this clear inconsistency problem? We shall briefly review the recent stream of economic literature devoted to this fundamental issue. We start with the basic non-convex adjustment costs story, more sophisticated concepts will be treated along the way.

2.1 Non-convex capital adjustment costs

This issue is very comprehensively treated by Caballero (1999), among others. Following this author, assume that a given firm has an optimal capital stock, K^* , which depends on the interest rate and on any profitability (exogenous) variable (possibly technological innovations). The crucial thing is the *specification* of the adjustment costs. If one aims at generating infrequent and lumpy investment patterns at the optimum, he should care about the functional form to assign to these costs. The traditional simple convex form is inadequate. In order to generate infrequent investment, the adjustment costs function should be chosen such that it increases sharply around the point of no adjustment. As mentioned by Caballero, a cost proportional to the size of the needed adjustment is enough. Now, this specification gives infrequency, but not lumpiness. To get the latter characteristic, there must be an advantage in bunching investment, and this can be achieved if for example adjustment requires a fixed cost. For a positive investment I , the associated adjustment cost is consequently: $c_f + c_v I$ where c_f and c_v are two positive constants. A similar adjustment costs function has to be set in case of disinvestment (when $I < 0$), including a positive fixed cost of disinvestment. We are in a typical situation where the adjustment technology exhibits **increasing returns**. For the relative importance of adjustment costs to be constant over time, the latter term is

usually multiplied by K^* .

How does the optimization model perform with this modified adjustment costs function? And how does the obtained demand for capital goods look like, in particular in relation with technical innovations? The main properties of the optimization problems are stated in Caballero (1999), section 3. The following points can be highlighted:

1. In such a model, there is room for **inaction**. This is a crucial departure from the standard models with quadratic adjustment costs. In such models, capital accumulation and investment paths are smooth in time, so there is no infrequent or lumpy investment episode. In the alternative model, things are very different. The intuitive reasoning behind is the following.¹ Call $Z = \frac{K}{K^*}$, a measure of capital imbalance. Assume that the actual capital imbalance is near the point which maximizes the value of the firm (roughly speaking the discounted sum of the present and (expected) future profits of the firm). Then, the firm may not have any incentive to pursue the adjustment because of the incurred adjustment costs. This is specially true for small adjustments because of the fixed costs. Hence, the firm may perfectly choose to be inactive in such a case. Indeed, it is possible to prove rigorously that there exists a non-empty range of inaction in the space of Z . More concretely, there exists a target point L such that there is no investment for $Z > L$, and a target point U such that there is no disinvestment for $Z < U$. Which ultimately means that there exists a range of inaction (L, U) . Infrequency and lumpiness can therefore be generated within this alternative framework.

2. Is the q-theory robust to such a "realistic" specification of adjustment costs? Recall that in the basic optimization setting, we get the following relationship between investment and (marginal) q: $q = 1 + C'(I)$, when the unit price of capital is equal to 1 ($s = 1$). In the quadratic case, *ie.* when $C(I) = bI^2$, where $b > 0$, we get a linear relationship between q and I . In the general convex case, we get an implicit monotonic functional relation between q and I : $I = \psi(q)$. To each value of q corresponds a single investment amount. Is this functional relationship preserved in the case of adjustment costs with increasing returns? The answer is no as demonstrated by Caballero and Leahy (1996). In effect, the relationship between marginal q and Z , the capital imbalance,

¹The reader interested in the exact mathematical solution can find all the technicalities in Caballero (1999). The technique makes use of dynamic programming in continuous time with the associated optimality principle.

ance, is not functional over the Z space in that the same value of q is associated with different investment values. And in the region of the Z space where this relationship is functional, it is highly nonlinear. So in the very best case, the q-theory only holds "locally" but the induced functional relationship between q and I is by no way linear.

This suggests two main points. First of all, the q-theory is typically a non-robust theory. Indeed, there exists a huge literature on this particular point. Many authors have studied the implications of different specifications of the adjustment costs departing from the initial quadratic formulation. Some have removed the fixed costs; others have added a strictly convex term to the adjustment functions. In some contributions, the monotonic relationship between q and investment is recovered but at the cost of less realistic generated investment patterns, notably in terms of lumpiness (as in the very well known Abel and Eberly's 1994 paper). Because of these robustness problems, the failures registered in its econometric implementation are not surprising at all. Second, a more favorable to the q-theory, these failures may be simply due to the use of linear regressions, as the "true" relationship between q and capital is probably highly nonlinear.

3. How do technological innovations enter this new investment set-up? Actually, these new micro-economically founded adjustment theories enrich in a considerable way the discussion on the effects of technological innovations (or any other external shock) on the demand for equipment. In the standard optimal control theory, there is no range for inaction. In the case of a technological improvement (raising the productivity of capital goods for example), q increases since it is a measure of the value to the firm of an additional unit of (new) equipment. As q goes up, investment is systematically stimulated, because q is monotonically related to I via the investment equation, $q = 1 + C'(I)$, under the strict convexity of the adjustment costs function. When a range of inaction (optimally) arises, a technical innovation does not necessarily trigger an investment boom.²

Let us have a closer look at this specific point. A careful reading of Caballero and Engel (1999) allows to notice that technological progress, purely disembodied in this theory, exclusively operates through the optimal capital stock, K^* , thus through the imbalance ratio Z . Indeed, neither the threshold, L nor the threshold U depends on technological progress: In Caballero and Engel (1999), both are function of the fraction of profits

²This may be true even in the absence of fixed costs. See Abel and Eberly (1994).

foregone due to capital stock adjustment, which is ultimately assumed to be randomly distributed.³ Thus, a technological improvement has essentially the virtue of raising the optimal capital stock, K^* , which for given K , lowers the capital imbalance Z since $Z = \frac{K}{K^*}$. Suppose that initially Z is in the range of inaction (L, U) . A small technological shock is unlikely to lower Z at a value below the threshold L . For investment to occur, ie. for Z to be shifted below L , the magnitude of the technological improvement should be big enough. This is one the reasons why technological diffusion is not instantaneous. Investment involves some non-negligible adjustment costs which makes it optimal sometimes to not act, to not invest. In such a case, the institutions have a role to play, and economic policy crucially matters. For example, when the technological improvement is not enough big to encourage investment, a further decrease in the interest rate (or any other component of the user cost of capital) may help the diffusion (by increasing K^* and then by lowering even more the capital imbalance Z).

Uncertainty and irreversibility are other factors that call for inaction and delayed adoption of innovative tools, as it is explained in the next sub-section.

2.2 Irreversibility and uncertainty

The literature relating investment and uncertainty has generated two different conclusions. In the one hand, the presence of constant returns to scale and symmetric adjustment costs have led to the conclusion that uncertainty increases the value of investment (see for instance Hartman, 1972, and Abel, 1983 and 1985)). In this set-up, the marginal value of capital is a convex function of the stochastic process: Jensen's inequality thus implies a higher demand for investment. On the other hand, the introduction of irreversibility gives rise to another different mechanism (Dixit and Pindyck, 1994, and Pindyck, 1988). Irreversibility of investment amounts to saying that undertaking investment projects results in some unrecoverable initial costs, the so-called sunk costs. Uncertainty on future benefits and costs of investment projects makes the resulting investment problem trickier. If we assume with Dixit and Pindyck that if the investment project is not undertaken today, the firms retain the **option** of undertaking the project tomorrow, there is a clear value of waiting: the firms have always the possibility to

³See page 8 of the article by Caballero and Engel (1999).

postpone investment tomorrow in order to learn more about present and future project payoffs. This value of waiting, this option of waiting, is the main characteristic of the above mentioned theories, and it has some crucial implications in terms of investment patterns (lumpiness, infrequency, as observed in micro data) and economic policy. We shall summarize the related stream of literature in the few following points.

1. As argued in Chirinko (1996), “...In the traditional optimal control model *à la* Jorgenson, investment is reversible because well functioning secondary markets exist or the rate at which firms wish to reduce the capital stock is less than the rate of depreciation, ie. gross investment is always positive...Moreover, in the traditional approach, there is no room for flexible timing in investment: Either the firms invest ($I > 0$) or they don’t, and in the latter case, it is implicitly assumed that the investment opportunity lost will never be recovered. The optimal investment rule giving the optimal capital stock is basically: Investment is undertaken if and only if the (expected) marginal profitability of capital, MPK, is bigger than a user cost of capital, which includes the interest rate (the discounting rate), the depreciation rate of capital, and the (expected) rate of change of the acquisition price of capital. This is exactly what may happen if the firm, initially at equilibrium, is affected by a positive technical innovation; the MPK curve is likely to be shifted upward, so that investment takes place. In Dixit-Pindyck’s models, the rule is not that simple. There is an option of waiting. Even if a technical innovation unambiguously shifts upward MPK, uncertainty, irreversibility plus time flexibility may induce the firm to wait, and not react to the innovation by investing, that is the threshold value of expected MPK above which the firm invests, is *a priori* significantly bigger than the typical user cost or discounting rate threshold values encountered in the traditional theory. To these typical terms, one has to add the value of waiting, which is in general a function of a measure of uncertainty, typically the variance of a stochastic price or technological variables, and of the actual levels of the latter variables, including the capital depreciation rate.⁴

It follows that investment patterns are potentially less smooth when one has to account for irreversibility under uncertainty. As in the models with non-convex adjustment costs seen above, there is room for inaction: Provided the flexibility of the investment decision

⁴The reader interested in the exact formula of the value of waiting can find the necessary material in Pindyck (1988).

timing, the firms can decide to not act for a while since there is a value of waiting, which generates the infrequency characteristic.

2. What are the theoretical implications of this approach as to investment patterns? As we have just said, irreversibility plus uncertainty and time flexibility implies that equipment purchases occur only in spurts. To be precise, investment occurs if the (expected) profitability of marginal investment is enough high to compensate the cost of capital and the value of waiting. This is likely to happen in very good times (for example, when the demand for the goods produced by the firms is very high using historical standards, as in Pindyck, 1988). But this is unlikely to happen for any good draw in the distribution of the stochastic environment. Typically the firms increase their productive capacity only periodically. These models usually have marginal increment, and are unable to generate lumpiness.

3. There is a much more important new direction in the irreversibility literature with respect to the traditional non-convex adjustment costs models: The role of **the rate of utilization of capital**. Allow the firms to choose this rate in presence of uncertainty, irreversibility and time flexibility, and forget about capital depreciation. The typical outcome is the following. In good times, there is little doubt that the optimal decision should be to fully utilize the productive capacity. In very good times, as we have just mentioned above, the firms additionally increase their capital stock. What happens in bad times? This crucial question is addressed in Dixit and Pindyck (1994), and before by Pindyck (1988) in a basic formal setting. In bad times, since investment is irreversible and capital depreciation is assumed to be zero, the capital stock held does not move. This inertia in the capital stock is coupled with a non constant optimal utilization rate. An adverse shock need not reduce this rate systematically. For the rate of utilization to fall, the adverse (demand and/or technological) shock should be of a very large magnitude. For moderate negative shocks, full utilization (and zero investment) is optimal. The rate of capacity utilization plays therefore a central role in shaping investment patterns when irreversibility and uncertainty matters, and this should be of interest for practitioners seeking for the best investment decision in such a context. Typical wisdom from this approach is that firms must reuse all the units, that's increase their rate of capacity utilization if possible, before investing. Certainly, this behavior is not always corroborated by the empirical evidence. In certain cases,

firms do invest even if they have not reached full capacity, which goes at odds with one of the main implications of the 1988 Pindyck's seminal work. This kind of behaviour is highlighted in several microeconometric studies (see for example Licandro et al. (2005) on Spanish data among many other firm level studies). Cruz and Pommeret (2010) show that accounting for investment-specific technological progress (via vintage capital modelling) is enough to explain this striking finding. Indeed, if investment is the exclusive vehicle of technological innovations and if a decisive technological upgrading is taking place, the decision to invest (often coupled with replacement of old and less productive equipment) is likely to be less intimately related to the rate of utilization control. We shall insist on the necessity to account for this feature of technological progress (that's embodiment) in Section III, especially in connection with the ICT burst.

4. The q -theory is generally non-robust to extensions of the basic model incorporating non-convex adjustment costs. When the benchmark model is extended to include uncertainty, irreversibility and flexibility in timing, then this non-robustness is much less clear, as it is brilliantly explained by Dixit and Pindyck in their book.⁵ True, there is no monotonic relationship between q and investment over the whole space of capital imbalance Z . But, in contrast to the model with non-convex adjustment costs where non-monotonicity may show up locally in the Z -space, the picture is simpler here: The Z space is divided in three regions where investment is respectively rising, falling or constant with increases in q . In other terms, there exist three distinct regimes but none shows up a non-monotonic relationship between q and investment. This leads many theorists, following Dixit and Pindyck, to argue that accounting for irreversibility and uncertainty does not only preserve the basic q -theory but it also allows to remedy the empirical failures of this theory. That is the usual tests do not consider the possible existence of a multiple regime (q, I) relationship. Their failure may come from this omission. While this claim is so far unproven, as correctly pointed out by Chirinko (1996), it gives an early idea about the complexity of the empirical debate surrounding the concepts of irreversibility, uncertainty and non-convex adjustment costs. The next sub-section addresses very briefly this issue, among others.

⁵The reader can find a complete proof of these claims in the quoted book. These properties are mathematically quite intuitive: The presence of a fixed cost has a much more damaging effect on the concavity of the value functions of the firms, arising in the considered dynamic programming problems.

2.3 Some remarks on the “new” investment theories

Some crucial issues remain to be addressed. First of all, if it is widely admitted that non-convex adjustment costs and/or irreversibility are much more consistent with observed investment behaviour at the plant level than the Jorgenson neoclassical model, it is crucial to study whether aggregation will not “kill” them. In other terms, it is important to assert neatly that non-convex adjustment costs and/or irreversibility have a first-order impact in explaining aggregate investment patterns. Second, it is important to examine if these new theories are not leaving in the dark, some crucial aspects of the investment decision; we shall argue in this respect that embodied technical progress, and more generally the vintage composition of the capital stock, are important but still insufficiently dealt with in these new theories.

1. With either non-convex adjustment costs or irreversibility, the investment patterns seem to be consistent with the empirical characteristics of micro adjustment as documented by Doms and Dunne (1998), namely infrequency and lumpiness. But as mentioned by Caballero (1999), the empirical corroboration of these simple adjustment rules is far from easy, as “...firms respond differently to similar imbalances over time and across firms”. This leads Caballero and Engel (1999) to construct a stochastic version of the model with non-convex adjustment costs, where the regions of inaction and adjustment are not deterministically set, the basic idea being that large imbalances are more likely to induce investment. A simple way to randomize the latter model is to assume that the fixed cost variable is stochastic. Then, the analysis relies on the so-called **hazard functions**, $H(Z)$, which describe the probability to adjust when capital imbalance (or any other convenient function of it) is equal to Z .

2. In their celebrated 1999 paper, Caballero and Engel provide the necessary material to estimate these hazard functions and more importantly, to aggregate them. For a given imbalance Z , it is demonstrated that the expected investment by any firm can be written as basically the product of the adjustment to be done and the probability for the firm to undertake it (namely $H(Z)$). Then aggregation follows in two steps. Provided a large number of firms exist in the sample (which is the case in the empirical studies conducted on US micro data), so that the law of large numbers prevails, one can first take average investment over the establishments of the sample having approximately

the same capital imbalance Z , as an estimate of expected investment (conditional to the level of imbalance). Then, using the above mentioned simple expression of expected investment in terms of the hazard function, one can precisely estimate the latter function. The second step simply requires averaging across all Z .⁶

3. The results obtained by Caballero, Engel and Haltiwanger (1995) (corroborated by further empirical studies) seem to confirm the importance of non-convexities and, incidentally of irreversibility, both at the micro and aggregate levels. The main result is that the hazard functions are clearly increasing consistently with the "new" investment theories emphasizing the role of non-convexities and irreversibility. In particular, expected investment rises more than proportionally with capital imbalance. The linear specifications, consistent with the traditional formulations of the user cost and Tobin's q theories, rather predict constant hazard functions, *ie.* the probability to adjust is the same whatever is the level of capital imbalance. The same conclusion is made at the aggregate level. Moreover, the estimated hazard functions are shown to be very low for negative adjustment, suggesting irreversibility.

4. Despite this plausible evidences, more empirical work should be done, particularly in order to corroborate the irreversibility hypothesis. It is out of question that irreversibility matters in some circumstances. But it is also true that secondary markets exist for many capital goods, and this is likely to alleviate the effect of the irreversibility constraint. According to Chirinko (1996), 45% of nonresidential equipment purchases in 1993 were for information processing and related equipment, and secondary markets exist for such capital goods. Such markets plausibly exist for other capital goods like transportation and related equipment (20% of 1993 nonresidential equipment purchases) or tractors and agricultural and construction machinery (5%). Naturally, to quantify precisely the extent of irreversibility, it is necessary to go a step further and estimate the gap between the acquisition and resale prices. This is still not systematically done. Undoubtedly, Caballero's work with Engel, Bertola and Haltiwanger is fundamental in that it shows theoretically and empirically how accounting for non-convexities and irreversibility can be crucial in understanding investment behavior at the firm level. However, an accurate quantification of the real effects of both is not easy to produce,

⁶See Caballero and Engel (1999) for more details on this elementary procedure, and an empirical implementation of it in Caballero, Engel and Haltiwanger(1999).

and Chirinko's objection is a good illustration of the reasonable doubts one can have about the recent investment theories.

5. Another questionable aspect of most of the models belonging to this literature stream is its treatment of technological progress. Technological choices affect capital accumulation exactly as in the early neoclassical theories, exclusively through the optimal stock of capital. However, it is now widely admitted that investing is also a technology choice because most innovations are embodied in capital goods. New capital goods are therefore likely to be more productive than old capital goods, and the age (or vintage) composition of the capital stock at all levels is potentially an important variable driving investment. This was recently pointed out in a seminal paper by Cooper, Haltiwanger and Power (1999). In contrast to Caballero and Engel, a new machine is more productive because of embodied technical change. Therefore, the age distribution of the capital stock does matter. Indeed, the hazard functions do no longer depend on the imbalance variable Z as in Caballero and Engel, but on the age of the capital stock and aggregate productivity. Cooper and his co-authors clearly show that the hazard functions are increasing with the age of the capital stock, which could be interpreted as a strong evidence in support of the role of embodiment in the investment decision. Moreover, ignoring the cross-sectional age distribution of capital is shown to yield predictable and non-negligible errors in forecasting changes in aggregate investment after large swings in aggregate investment. In the next section, we provide a further empirical evidence in favor of the embodiment hypothesis. We shall review afterwards the new (rather) literature satisfactorily placing embodiment and vintage effects at the heart of investment and growth theory, specially after the rise of information and communication technologies in the 90s.

3 Vintage capital, embodied technical change and the 90's burst in ICT investment

As we have repeatedly mentioned before, technological progress is traditionally treated as part of the environment surrounding the firms just like government or weather. In such a context, a capital subsidy produces the same investment stimulus as an innovation

boosting the marginal profitability of capital. The non-convexities and irreversibility theories seen just above enrich considerably the analysis by showing that such fiscal and technical positive shocks are not necessarily followed by a rise in investment, as the simple (quasi-linear) traditional theories predict. But these new theories do not treat technological innovations in a very innovative way indeed, with the exception of Cooper, Haltiwanger and Power (1999).

The recent burst in ICT investment and its tremendous impact on the aggregate economy makes it necessary to think differently about how new technologies are brought into the market. In this specific case, it is clear that investment is the unique way to take advantage of the new technologies. It turns out that this is also the case for many other capital goods. When a firm acquires a machine, it also typically acquires a technology. Is it relevant to make the difference between embodied and disembodied technological progress? Is the embodiment characteristic so important to account for? The answer is nowadays clear: yes. It has been shown that around two thirds of the economic growth of the US economy over the period 1950-1990 is due to embodied technological progress (Greenwood, Hercowitz and Krusell, 1997). Since embodied technical progress has some specific implications at both the micro and macro level, it appears worthwhile to develop new approaches to investment, technological progress and growth. We summarize the main ideas of this recent research line in the following points. More details, including implications outside investment theory, can be found in Boucekkine et al. (2011).

3.1 The basic framework

There are basically two alternative strategies to model embodiment. The first one is extremely simple. It is mainly based on the concept of the relative price of capital, but it does not seem to be sufficiently comprehensive to capture all the implications of embodiment at the micro level. The second one exploits explicitly a vintage structure and as such, it is more suitable to deal with investment behavior at the plant level.

1. The main idea underlying the first strategy is the following: Embodied technical progress shows up specifically in the declining pattern of the relative price of capital, *ie.* the price of capital goods in terms of consumption goods. This trend is impressive in the case of computers (an average decline rate of about 20% per year from 1990 to 1996

in the USA) but it is also observable in the aggregate, when one computes the evolution of a price index of capital in terms of a price index of consumption goods. And it traces back probably to the mid-seventies after the first oil shock.

Recall that the optimal capital accumulation rule in the basic Jorgenson model is

$$p \text{ MPK} = s \left(\delta + r - \frac{\dot{s}}{s} \right),$$

with p the output price, s the price of capital, δ the capital depreciation rate and r the interest rate. Assume for sake of simplicity that $p = 1$, so that s actually measures the relative price of capital. An improvement in the disembodied component of technological progress propagates directly via MPK . An acceleration in the rate of embodied technical change is basically measured by a drop in s , namely by $\frac{\dot{s}}{s} < 0$. Note that such a drop implies that the resale price is lower than the acquisition price of the capital goods, which tends to increase the user cost of capital. This features the famous **obsolescence mechanism** at work when technological progress is embodied, which was studied in details by Solow in 1960, and more recently in an optimal control set-up by Boucekkine, del Rio and Licandro (2003).

Will a drop in the relative price of capital stimulate equipment purchases, and through which channels if so? A priori, investment reaction is ambiguous since the user cost of capital, $c = s \left(\delta + r - \frac{\dot{s}}{s} \right)$ is affected by two opposite effects: a negative level effect (via the first term s) and the positive effect arising from the obsolescence costs (the term $\frac{\dot{s}}{s} < 0$). However, a truly rapid acceleration of the rate of decline of the relative price of capital should lower the user cost capital in the short run, inducing a massive accumulation of capital, as experienced by the US economy during the ICT boom episode. This is precisely the famous **capital deepening** engine of investment and growth, to which many analysts (notably, Gordon, 1999) attribute the impressive performances of the US economy during this episode. There is another and much more powerful reason to believe that an acceleration in the rate of embodied technical change can boost equipment purchases: One may think that the acquisition of more efficient and reliable machines will end up shifting upward the MPK curve.⁷ This **modernization channel** is at the heart of the current debate on the viability of the New Economy (see Gordon, 1999, again, and Boucekkine, del Rio and Licandro, 2003 and 2005).

⁷Recall that an acceleration in disembodied technical progress yields directly this shift.

To conclude, one should keep the idea that the (very) rapid decline in the relative price of capital should undeniably matter significantly in shaping the investment decision, as the recent ICT boom in the US indicates. Hence, in contrast to the recurrent finding in the empirical investment literature according to which prices do not matter, one should expect to identify a much tighter relationship between the cost of capital and equipment purchases from the last decade as the relative price of computers sharply decreases, and ICT equipment purchases as a fraction of total capital expenditures markedly go up.

2. In the previous set-up, obsolescence operates through the loss in value of a fraction of the installed capital stock as the new capital goods embody the latest technological advances and are likely to be much more productive. One may legitimately think that a natural outcome of obsolescence is the scrapping of the oldest and least efficient machines. Curiously this does not happen in the previous set-up. All the capital goods are held for ever though the amount of labor assigned to a given vintage of capital tends to zero as times passes.⁸ Overall in such models, the vintage structure is not very active. Since the early 90's, many models have been proposed to get rid of this defect. Naturally the vintage approach is analytically much more demanding since capital is no longer homogenous in such an approach. A very simple description of a typical economic vintage model can be given to present the ideas. The technical details can be found in Malcomson (1975), Van Hiltten (1991), Boucekkine, Germain and Licandro (1997), and Boucekkine, del Rio and Licandro (1999).

The vintage capital structure is introduced as follows. At any date t , different vintages of capital coexist. Call v the vint

age index: At t , typically the vintage index goes from $t - T(t)$ to t , where $T(t)$ is age of the oldest equipment still in use at t . Assume that a unit of capital of vintage v increases output at t by $y(v, t)$ with the corresponding operation cost $c(v, t)$ at t . If $J(t)$ is the expected lifetime of the new capital goods at t , then the expected discounted profits from purchasing a unit of new equipment at t is:

$$\int_t^{t+J(t)} (y(t, \tau) - c(t, \tau)) e^{-r(\tau-t)} d\tau,$$

where r is the interest rate (assumed constant for sake of simplicity). Under perfect

⁸This is essentially what happens in the Solow vintage capital model (1960), underlying the model seen just above.

foresight, namely in the absence of any uncertainty, we have additionally the identity $J(t) = T(t + J(t))$. Embodied technical progress can be modelled by assuming that new vintages either are less costly to operate, that is $c(v, t) > c(vv, t)$ if and only if $v < vv$, or more productive, $y(v, t) < y(vv, t)$ if and only if $v < vv$, or both.

The optimality condition for a strictly positive and finite investment in new equipment to occur equalizes the expected discounted profit given just above and the acquisition price of this new equipment. Assume that $s = 1$ at t , then the optimality condition is simply:

$$\int_t^{t+J(t)} (y(t, \tau) - c(t, \tau)) e^{-r(\tau-t)} d\tau = 1.$$

A typical case studied in the economic literature is the case of operating cost saving technical progress. Whatever is the vintage index, the increment in output is the same but operating a new vintage costs less either in terms of labor or energy for example. In such a case and under further mathematical conditions on the cost function, one can prove that the optimal lifetime of machines is constant over time: $T(t) = J(t) = T^*$, $\forall t$, where T^* is a well specified constant.⁹ That is, the optimal scrapping time is constant over time, a result well known in the management literature as the Terborgh-Smith property (see Malcomson, 1975). The capital goods produced and acquired at t get obsolete at $t + T^*$, and are scrapped and replaced (ideally) by the vintages produced at $t + T^*$. In such a case, replacement investment (to be differentiated from the investment behavior consisting in augmenting the capacity of a firm, studied in the previous sections) is likely to be periodic, reproducing the infrequency and lumpiness characteristics of investment at the plant level.

Therefore, two main implications can be drawn from the canonical vintage model described above. First of all, it is possible to build a vintage theory comprehensive enough to understand how and when a firm decides to throw out a machine and to replace it by a more recent one. In particular, it is possible to identify the main determinants of the lifetime of capital goods and the corresponding average age of capital in the aggregate. A simple illustration helps understanding why the theory is so comfortable in this respect. Consider an increase in the interest rate. Such a shock decreases the left hand side of the optimality condition written above while the right hand side is constant. The

⁹The reader interested in the way the constant is computed can find the needed mathematics in Van Hilten (1991), and Boucekkine, Germain and Licandro (1997).

optimal lifetime $J(t)$ should rise to re-establish equality. So an increase in the interest rate delays the scrapping of old machines, which is by no way surprising since a rise in r augments the opportunity cost of investing and requires a longer utilization of the machines to compensate this extra cost. Using simple analytical tools, one could indeed derive an accurate characterization of the optimal age distribution of machines mainly in terms of the parameters of the cost and production functions, which may be empirically tested.¹⁰

Second, we have also mentioned that the same set-up allows for a deep theoretical inspection into how replacement investment is performed by the firms. It turns out that since in many simple but reasonable cases, the optimal scrapping time is constant, this theory produces the stylized facts of investment at the plant level, as documented by Doms and Dunne, infrequency and lumpiness.¹¹

3.2 Macroeconomic implications: Embodied technological change and the growth process

The macroeconomic implications can be summarized in three points.

1. Can we talk about a macroeconomic vintage effect? It is not a simple question. The results stated just above are valid at a firm level. Each firm decides about its optimal replacement policy given the technological trends. To rigorously assess the relevance of this theory at the macro level, one should resort to aggregation. There is a much more direct way to detect a vintage effect. According to vintage models, the new generations of capital are more efficient and more productive. Hence, it is in principle worthwhile to shorten the lifetime of machines so as to take advantage of the most recent technological advances. If this is true, one may detect a very significant negative correlation between the average age of capital in the considered sample of firms (or even at the macro-economy) and the growth rate of aggregate output. This is referred to as the **vintage**

¹⁰Another determinant of capital lifetime, not directly related to embodiment, but empirically relevant is capital maintenance, which has broad micro and macroeconomic implications on investment, see Albonico et al. (2014). It's not problematic to introduce such an important ingredient in vintage capital settings as demonstrated by Saglam and Veliov (2008) and Boucekkine et al. (2010).

¹¹Again, this is rigorously demonstrated in Boucekkine, Germain and Licandro (1997) and Boucekkine, del Río and Licandro (1999).

effect in the macroeconomic literature. A theoretical foundation for this effect in an optimal control set-up can be found in Boucekkine *et al.* (1998). An early empirical assessment of it has been provided by Wolff (1996) on the US economy. According to Wolff, the vintage effect is strongly effective in the US economy. A more recent assessment on the vintage effect on TFP growth, again on US data, has been provided by Gittleman et al. (2006). The authors show that the rigorous accounting of the vintage effect does prompt an upward correction of measured productivity growth in times of an aging stock of capital. This ultimately points at an important point: Treating the capital stock as an homogenous block without accounting **rigorously** for its age distribution may be highly misleading in interpreting and quantitatively characterizing GDP and TFP growth experience of a country.

2. Concerning the aggregation of the replacement decisions and its impact on the patterns of aggregate investment, some very nice contributions have been done in the past few years. The most representative are certainly Adda and Cooper (2000), and Cooper, Haltiwanger and Power (1999). The main result brought out by these contributions is that aggregation does not eliminate the lumpiness and infrequency characteristics of investment patterns observed at the micro level.¹² One may go a step further and ask why the aggregation of individual investment patterns with a priori distinct periodicity features (due to a priori different scrapping time decisions) does not result in smooth aggregate investment dynamics. The main reason put forward by some authors is a kind of induced synchronization of scrapping decisions under aggregate shocks. That is, heterogeneous firms may be induced to take more or less the same timing of scrapping when they are submitted to the same aggregate shock. In the Adda and Cooper contribution for example, the resulting non-monotonic aggregate investment paths come from the application of scrappage subsidies by two successive French governments in a limited interval of time. Broadly speaking, this argument ultimately means that the aggregate shocks are more important than the idiosyncratic shocks in the scrapping decisions, a claim that certainly requires further corroboration.

3. Another important line of research, which has applied the previous investment models with vintage capital and/or embodied technical change to investigate whether an

¹²The reader can notice that this outcome is highly consistent with the aggregation results depicted in Caballero, Engel and Haltiwanger (1995) for example.

economic growth regime based on ICT equipment is sustainable in the long run. It is quite easy to see why those models are suitable to deal with the latter question: The technological advances conveyed by ICT are embodied in nature, and the replacement decision of the obsolete ICT tools is a key issue when one has to conduct a cost (obsolescence costs)/benefit (modernization) analysis of an economic growth regime driven by ICT. The important theoretical contributions regarding this issue are Krusell (1998), and Greenwood and Yorokoglu (1997); a much more empirical assessment is given by Gordon (1999). One of the main contributions of this literature is the incorporation into the benchmark vintage model seen above of the so-called **adoption costs**. In the benchmark model, when a machine gets obsolete, it is replaced without cost (except the acquisition price to pay) by a machine of the most recent vintage. However, as it is stated in Greenwood and Yorokoglu (1997), efficiently operating the new machines cannot be instantaneous and requires time since these machines eventually embody some innovative tools that may not be so easy to fully exploit from the acquisition date.¹³ For example, it could be the case that specific skills are needed to run efficiently the new machines, which induce the firms to spend an extra money in facilitating the adoption of these new technologies. In such a context, innovations can yield a productivity slowdown at least in the short run. Labor productivity and even total factor productivity may go down just after the costly adoption of the new technologies, and they would only recover after a relatively long period of time (some decades in the case of a radical innovation), as studied in Greenwood and Yorokoglu. In such a case, innovations will not be immediately followed by productivity improvements, as it is the case in the standard optimal control investment models. The tremendous rise of ICT investment from the early 90's has other crucial empirical consequences as for the validation of these traditional models, as it is explained briefly in the next sub-section.

3.3 More on the empirical ground: How to handle the burst in ICT investment

This sub-section is entirely based on the work of Tevlin and Whelan (2003). The empirical investment papers seem to deny any significant role to price variables and Tobin's

¹³The reader can notice the parallelism between the adjustment costs in the investment theories with disembodied technical progress and the adoption costs considered in the vintage approach.

q in explaining investment, specially in the 80's (see Chirinko's survey in 1993). Is this diagnosis acceptable for the more recent period, the 90's, where the relative price of capital has sharply decreased, following the even sharper decrease in the price of ICT equipment and the resulting massive investment in this type of equipment? For Tevlin and Whelan, the answer should be no. In particular, the user cost model should work during this episode. In order to make this property apparent however, one should treat properly some specific issues precisely coming from the very specific ICT boom episode in the 90's. First of all, capital depreciation should be seriously estimated (recall that the rate of capital depreciation enters the expression of the user cost of capital). Most empirical studies have tended to ignore the effects of capital depreciation, by assuming for example a constant pattern over time. This is definitely not true in the recent boom as the rise of ICT has been accompanied by a rise in the depreciation rate.¹⁴ This increasing depreciation rate is shown by Tevlin and Whelan to have a first-order explanatory power of the recent trends in equipment investment.

However, to study this aspect properly, one has to take into account that the depreciation rates vary widely across different types of equipment. **Aggregation crucially matters.** In particular, the depreciation rate of ICT equipment is much higher than the depreciation rate of non-ICT equipment. The main contribution of Tevlin and Whelan is precisely to show "...that a two equation system for net and gross investment in computing and non-computing equipment, estimated through 1989, is capable of explaining the magnitude and pattern of the US equipment investment boom of the 1990's, while **aggregate models completely fail**".

4 Concluding remarks

In this survey, we have tried to pick up the main ideas and concepts which have prevailed in the recent theoretical and empirical investment literature. We have drawn several lessons along the way. First of all, it is fair to acknowledge that some dramatic advances have been made in the 1990s thanks to the efforts of some research teams. In particular, the implications of non-convex capital adjustment schemes are now much

¹⁴Tevlin and Whelan report an acceleration of the (aggregate) depreciation rate from 0.13 in 1989 to 0.16 in 1997.

better understood. Nonetheless, this new literature has not satisfactorily accounted for the investment-specific nature of technical progress, with some very few exceptions. We do believe that the recent technological trends, notably the rise of ICT, have a heavy impact on the way the investment decision is taken and is to be taken. This in turn should imply the reconsideration of many empirical results, and a more careful modelling strategy taking into account the price variables and scrupulously choosing the most appropriate level of (dis)aggregation.

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